Interactions of Particles with Flow Structures in Turbulent Channel Flows

Amir A. Mofakham and Goodarz Ahmadi

Department of Mechanical and Aeronautical Engineering
Clarkson University, Potsdam, NY

John McLaughlin

Department of Chemical and Biomolecular Engineering
Clarkson University, Potsdam, NY

August 6, 2019

Outline

- **Flow Simulations (DNS)**
  - Geometry and boundary condition
  - Governing equations
- **Particle Simulations**
  - Governing equations
- **Results**
  - Evolution of near wall coherent structure
  - Time and space evolutions
- **Conclusions**

Methodology: Fluid Flow

Direct Numerical Simulation (DNS)

❖Pseudo-Spectral code

❖Solves the Navier-Stokes equations

$$\frac{\partial \mathbf{u}_f}{\partial t} + \mathbf{u}_f \cdot \nabla \mathbf{u}_f = -\frac{1}{\rho_f}\nabla P + \frac{1}{\mathrm{Re}_L}\nabla^2 \mathbf{u}_f$$

$$\nabla \cdot \mathbf{u}_f = 0$$

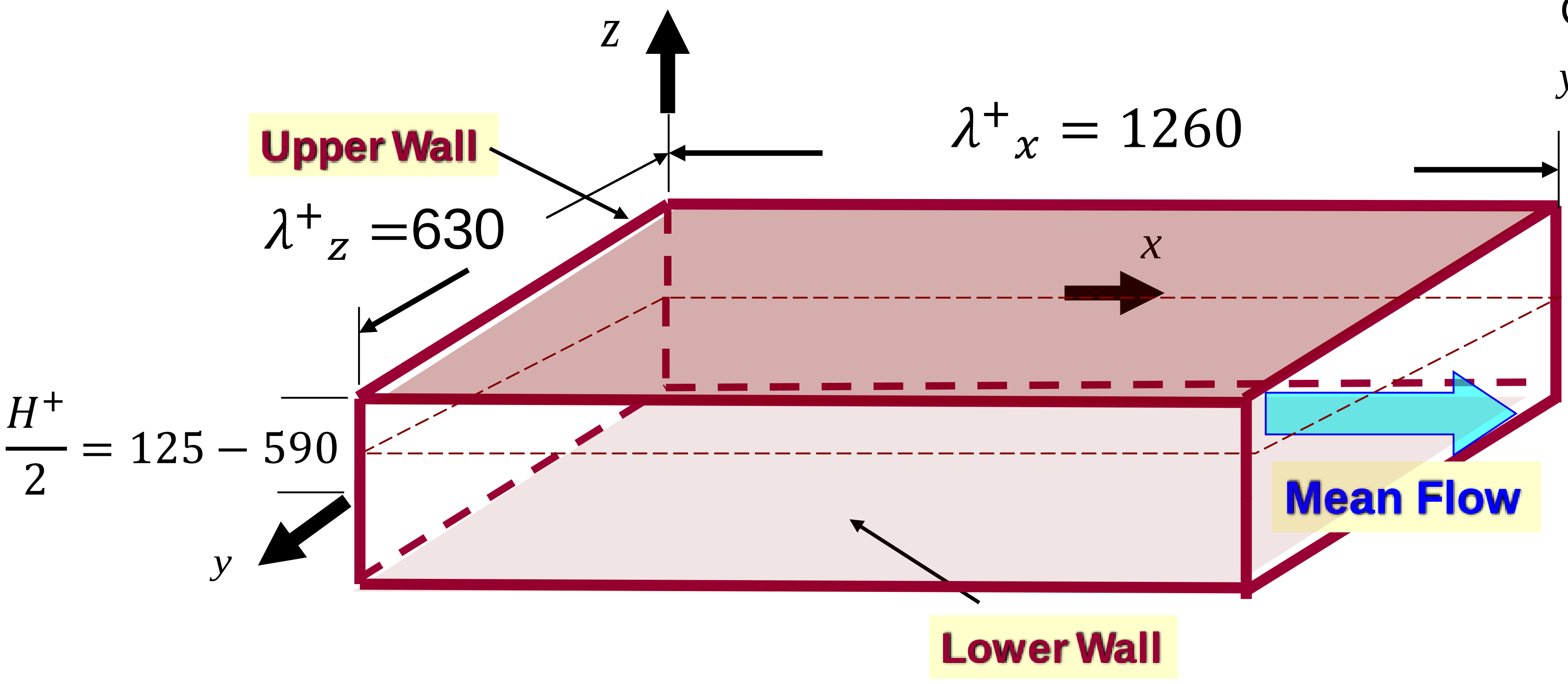
❖Streamwise and spanwise velocities are expanded by Fourier series

❖The normalized velocities are expanded by Chebyshev series

Methodology: Fluid Flow

Boundary Conditions:

$$\begin{cases} u^+ = 0, \quad y = \pm H^+/2 \\ u^+(x^+ + \lambda_x^+, y^+, z^+ + \lambda_z^+, t^+) = u^+(x^+, y^+, z^+, t^+) \end{cases}$$



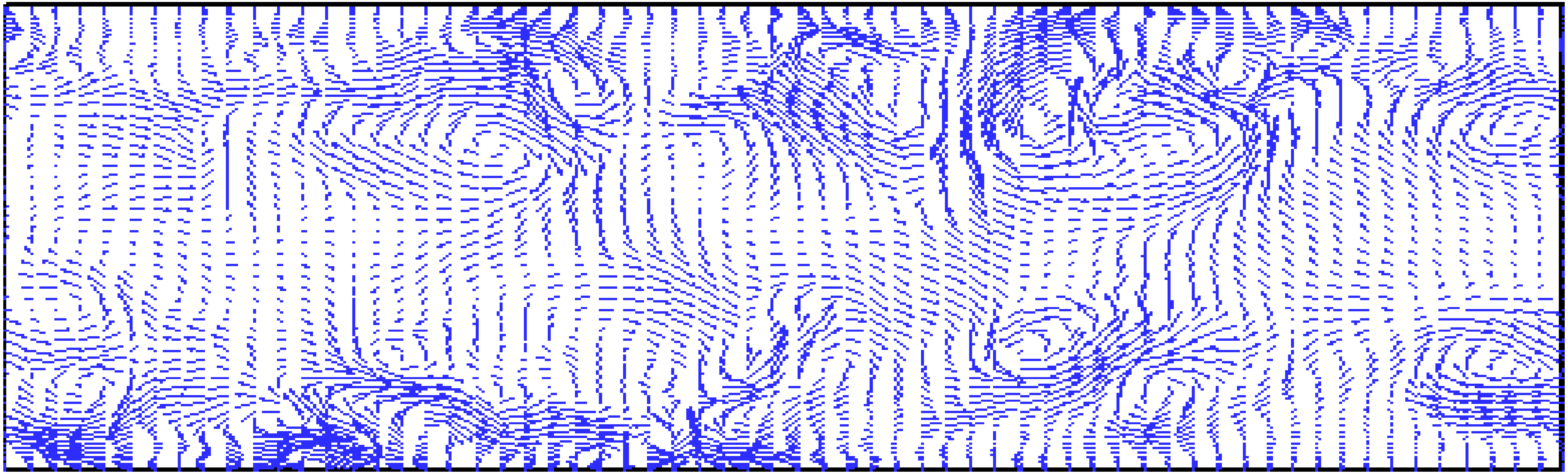
Gridding

$nx = 128, ny = 129, nz = 64$

1,056,768 cells

Chebyshev series

$$y_i^+ = \frac{H^+}{2}\cos(\pi i / M), \quad 0 \le i \le M$$



Eulerian-Lagrangian Method

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Wall units: $\overrightarrow{X^+} = \frac{\vec{X}u^*}{\nu}$ $t^+ = \frac{tu^{*2}}{\nu}$ $\overrightarrow{u^+} = \frac{\vec{u}}{u^*}$

Particle equation of motion:

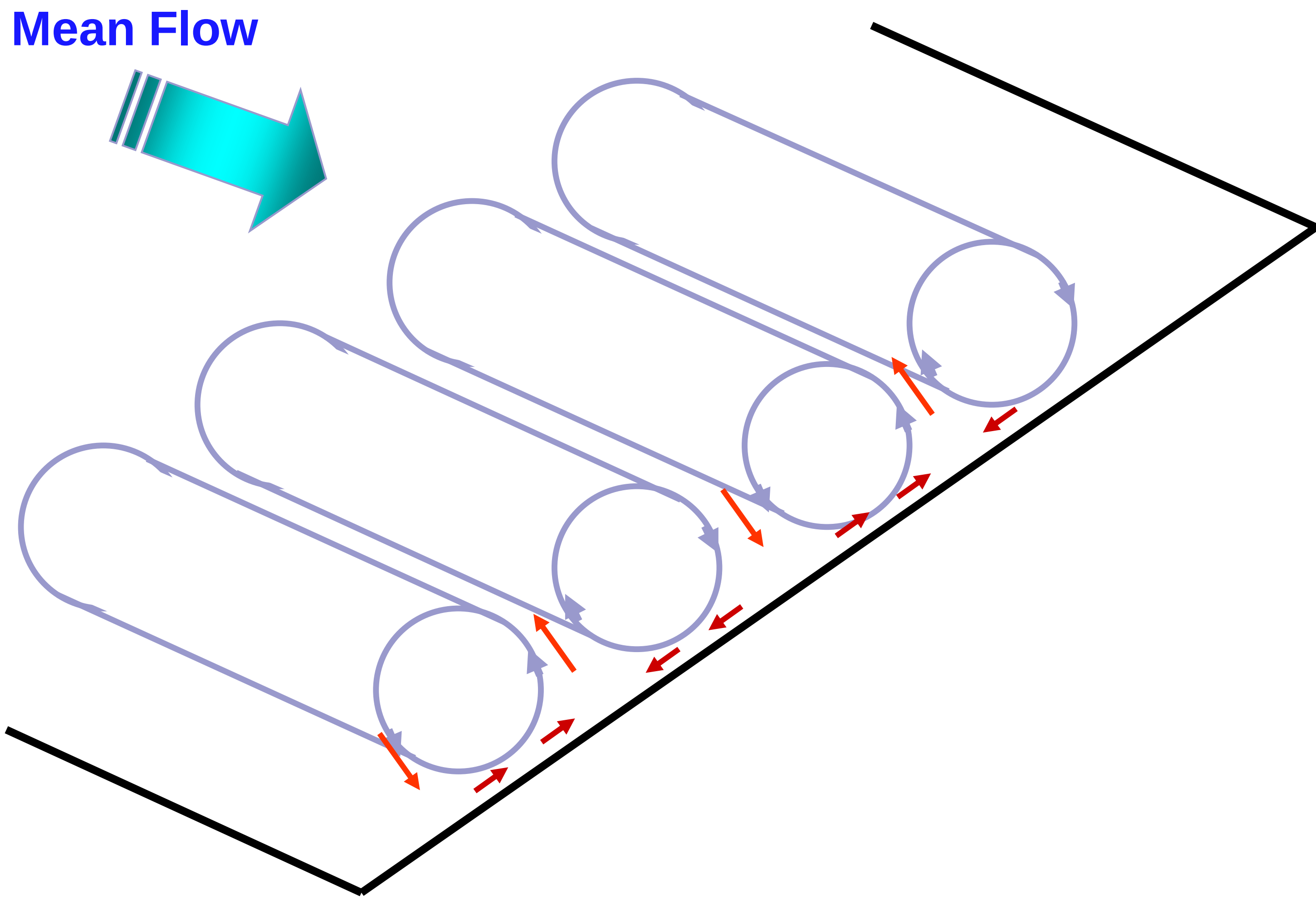
$$\begin{cases} \frac{d\overrightarrow{u_p^+}}{dt^+} = \underbrace{C_D F_D^+}_{\text{Drag force}} + \underbrace{F_l^+}_{\text{Lift Force}} + \underbrace{\overrightarrow{n^+}(t^+)}_{\text{Brownian motion}} \\ \frac{d\overrightarrow{x_p^+}}{dt^+} = \overrightarrow{u_p^+} \end{cases}$$

Drag coefficient:

$$CD = \begin{cases} 1 + 0.1875Re_p & Re \le 0.01 \\ 1 + 0.1315Re_p^{0.82+0.0217\,ln(Re_p)} & 0.01 \le Re_p \le 20 \end{cases}$$

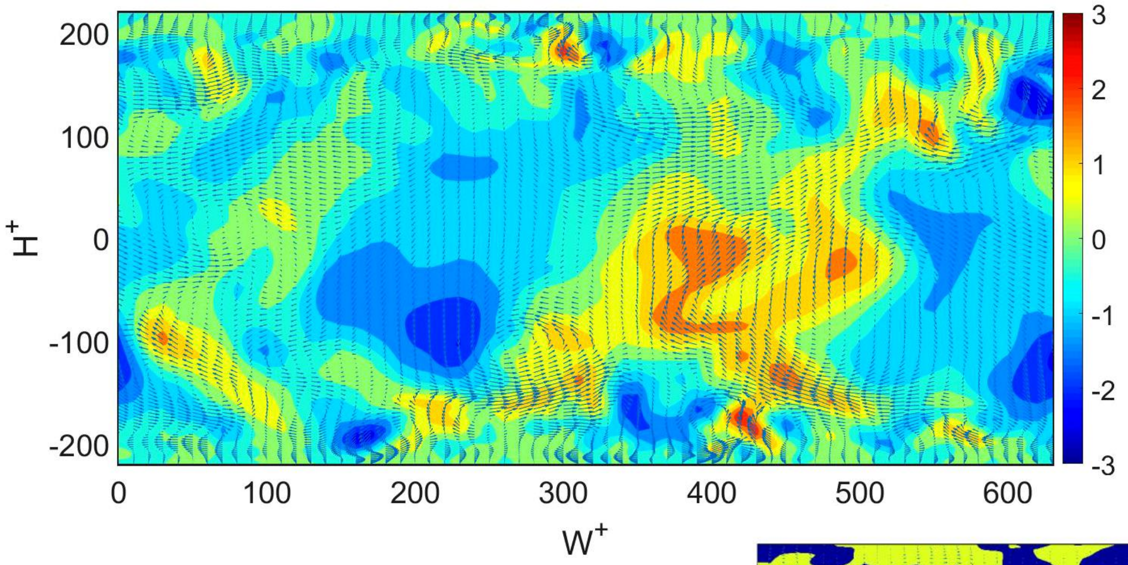
Coherent Wall Vortices

- Counter rotating vertices
- Elongated along the streamwise direction
- 100 wall units distance spacing
- Burst and inrush events

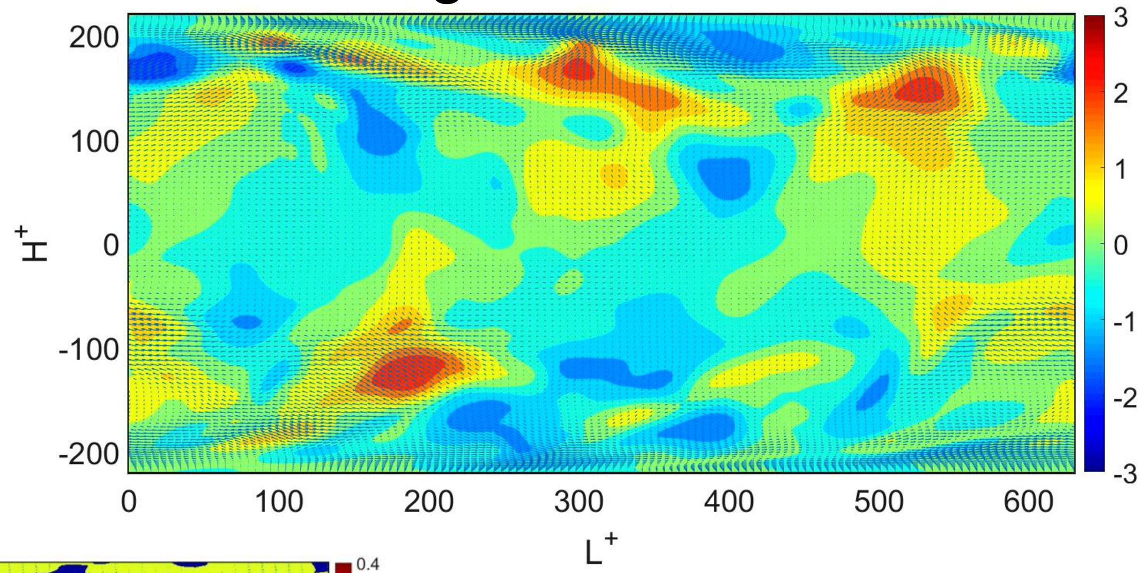


Normal Velocity and Vorticity Contours

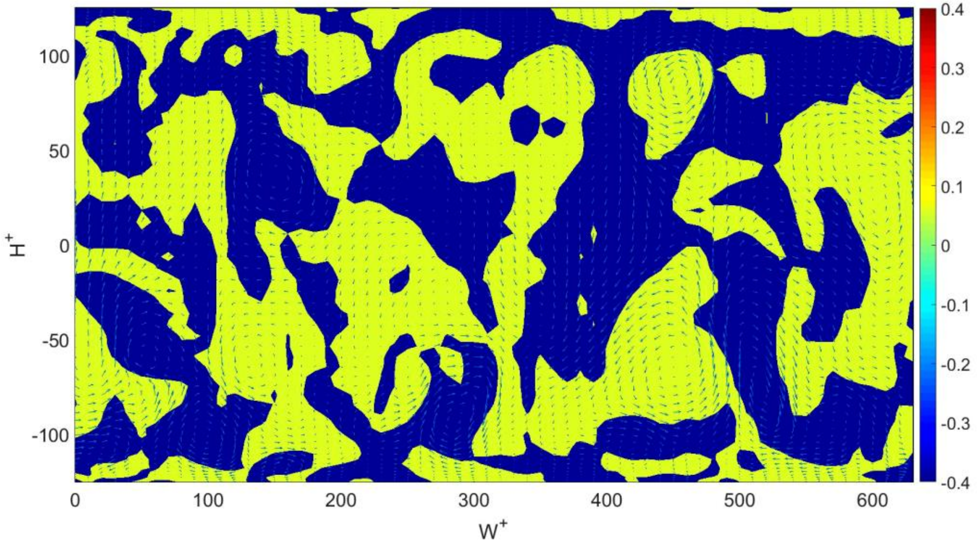
At a Cross Section



Along the channel



Time Variations



Vorticity Contours

Velocity Contours on Planes Parallel to Walls

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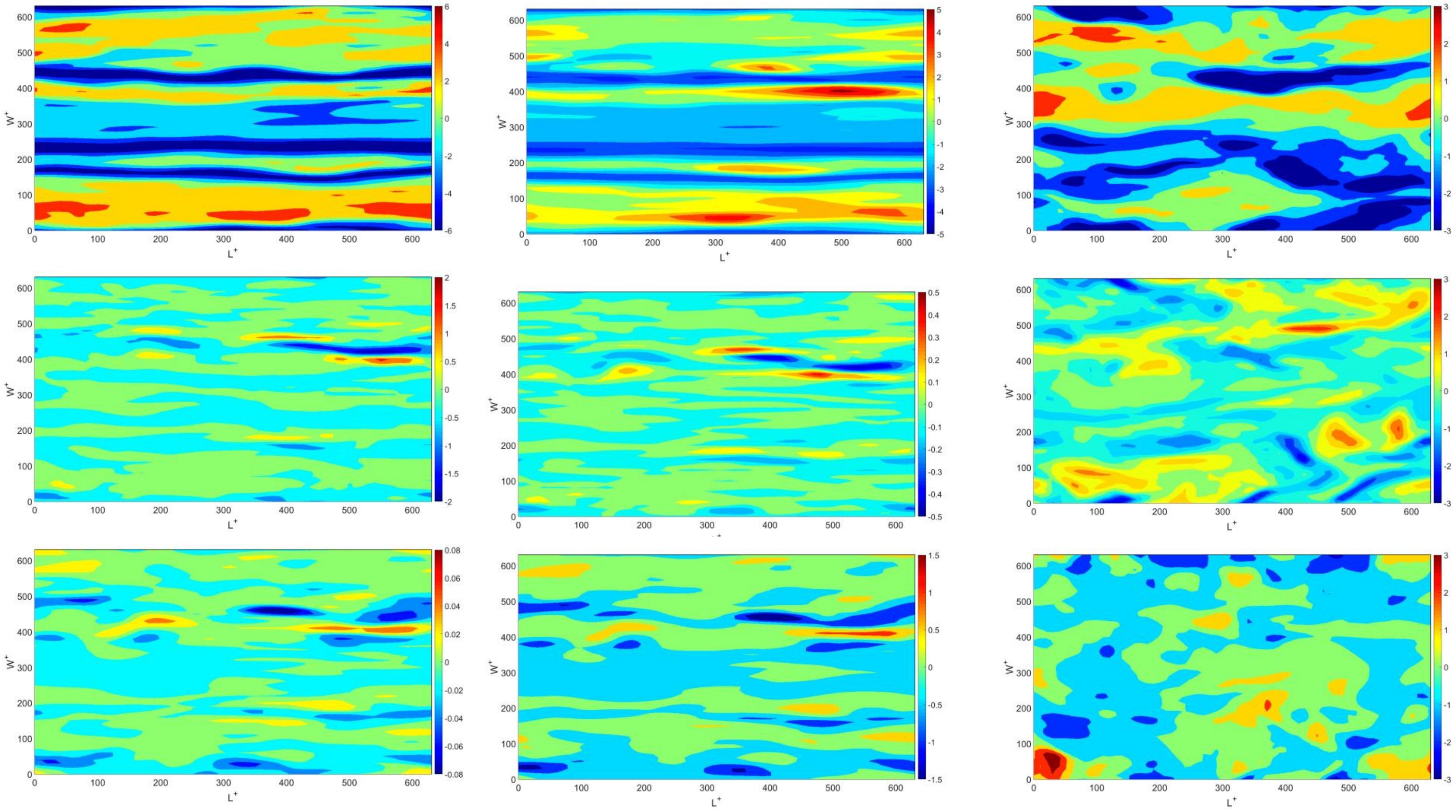
Time Variations

Y+=1.35 | Y+=5.38 | Y+=77.16

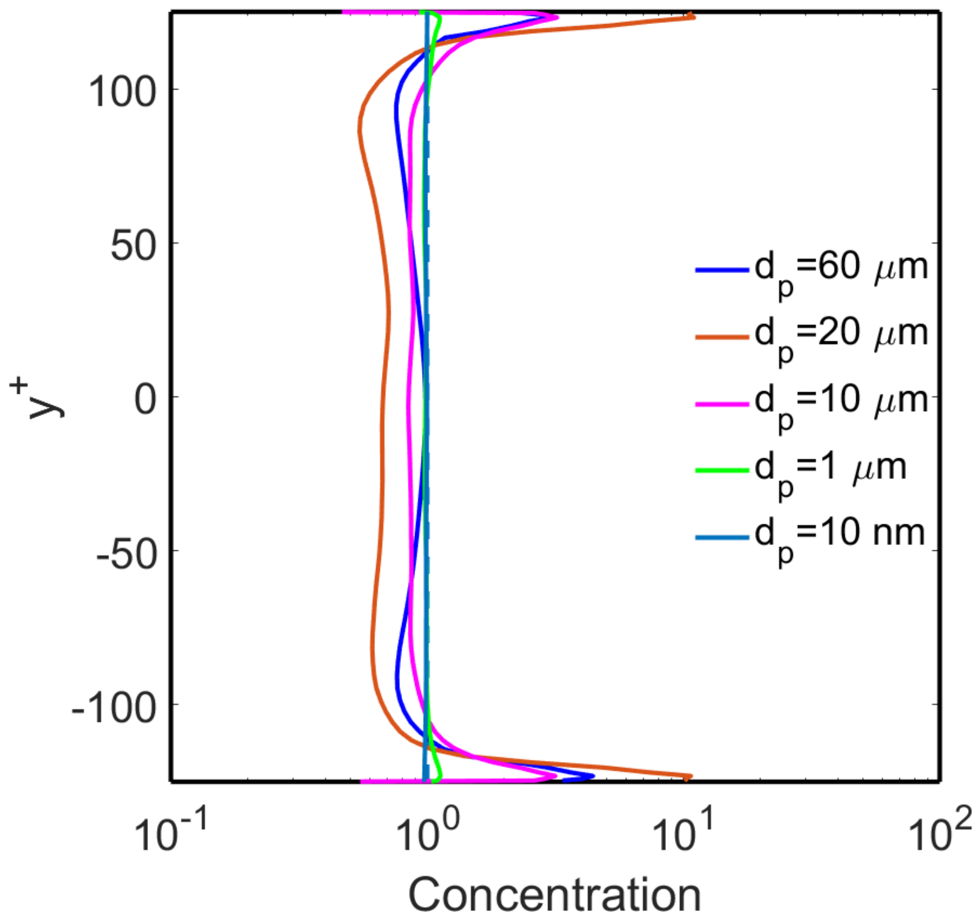


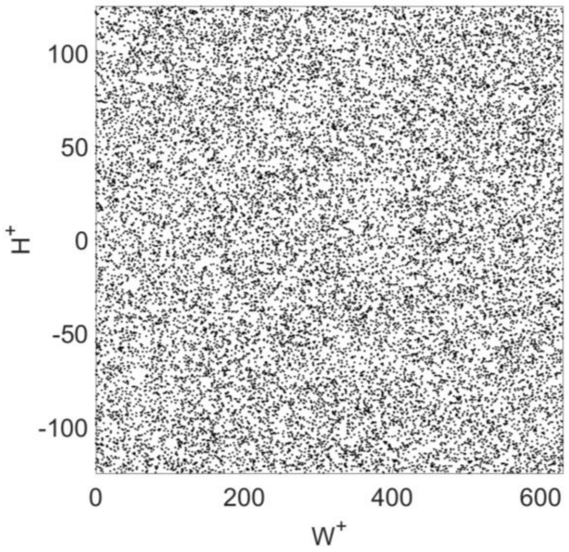
U Velocity

V Velocity

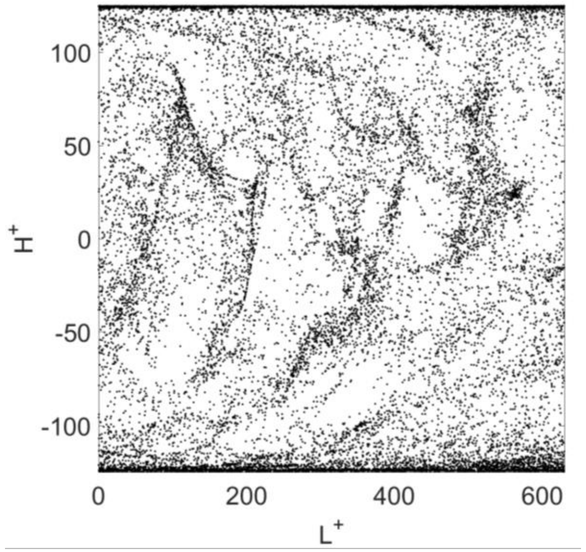
W Velocity

Concentration Profiles



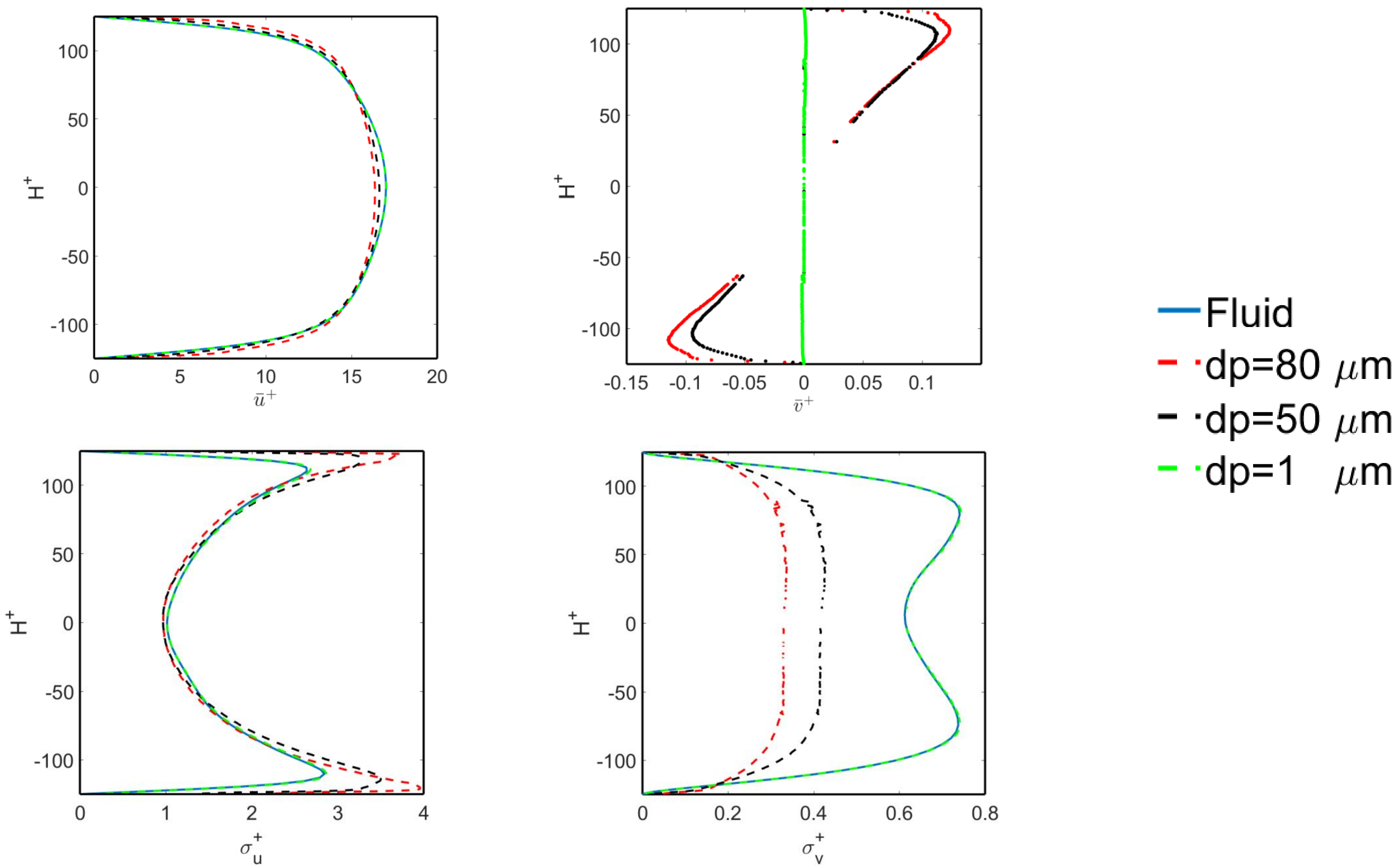


$d_p = 10\ nm$



$d_p = 20\ \mu m$

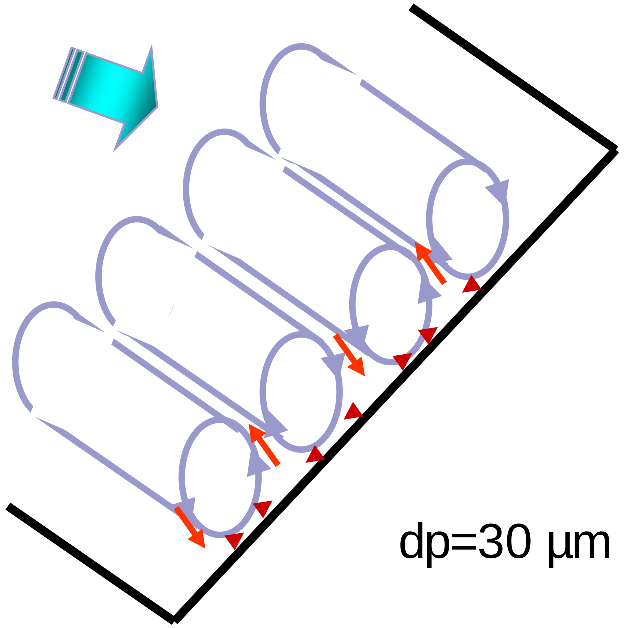
Velocity Profiles

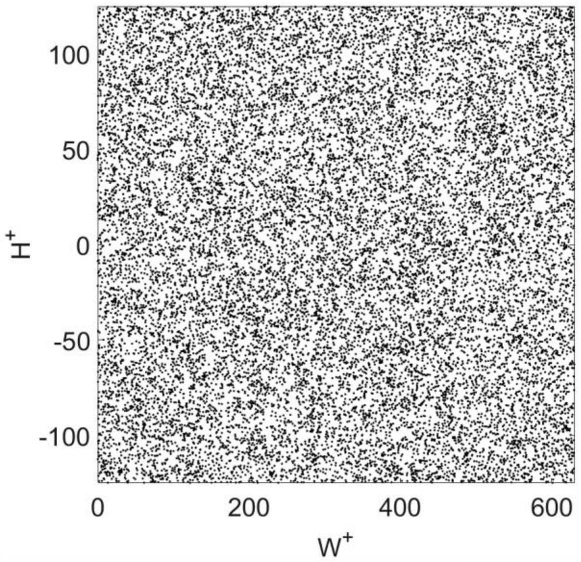


Streamwise Direction

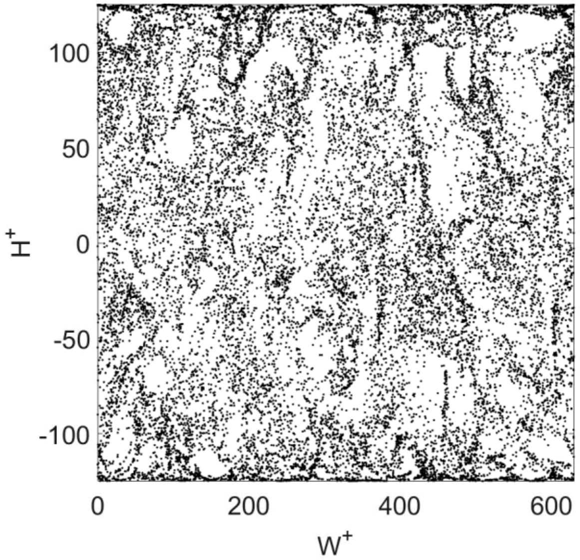
Space Variations

dp=1 μm

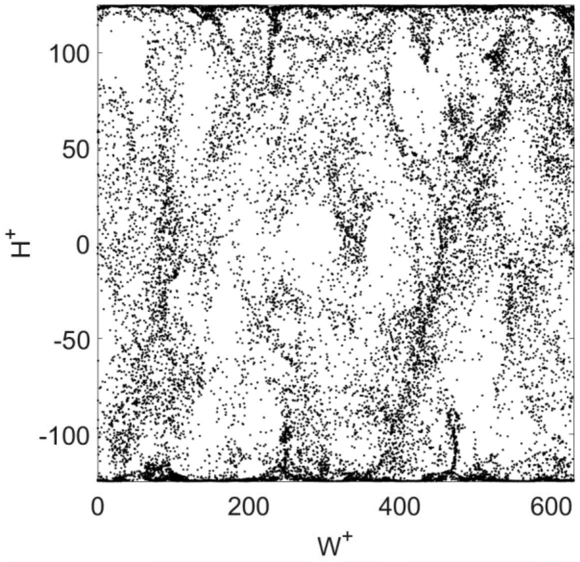




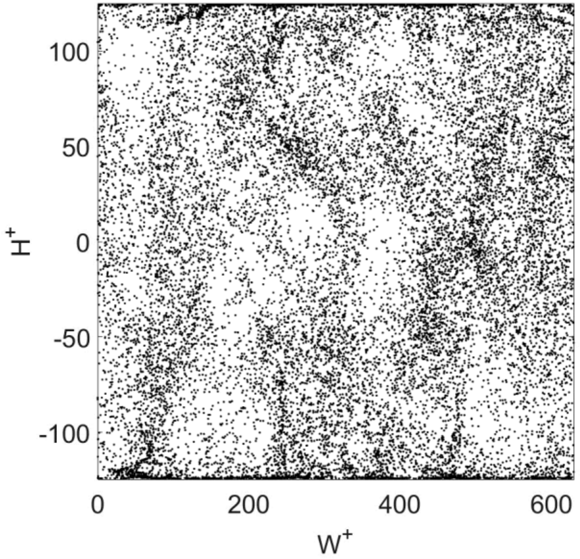
dp=10 μm



dp=30 μm

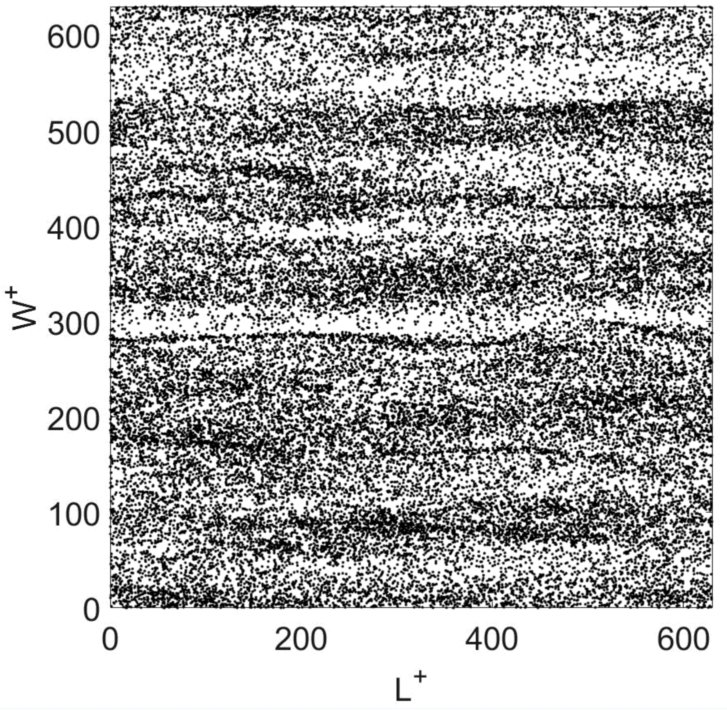


dp=60 μm

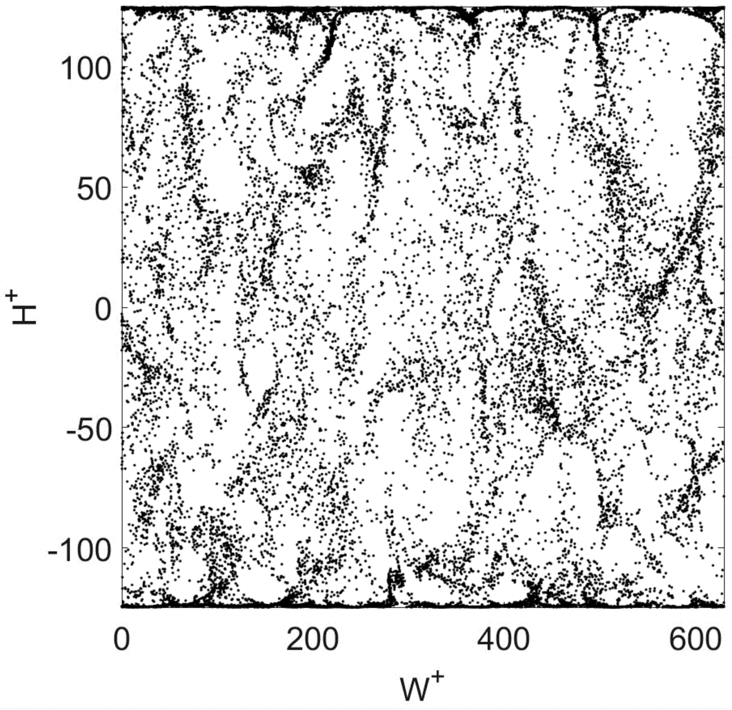


Preferential Concentration of 20 μm particles

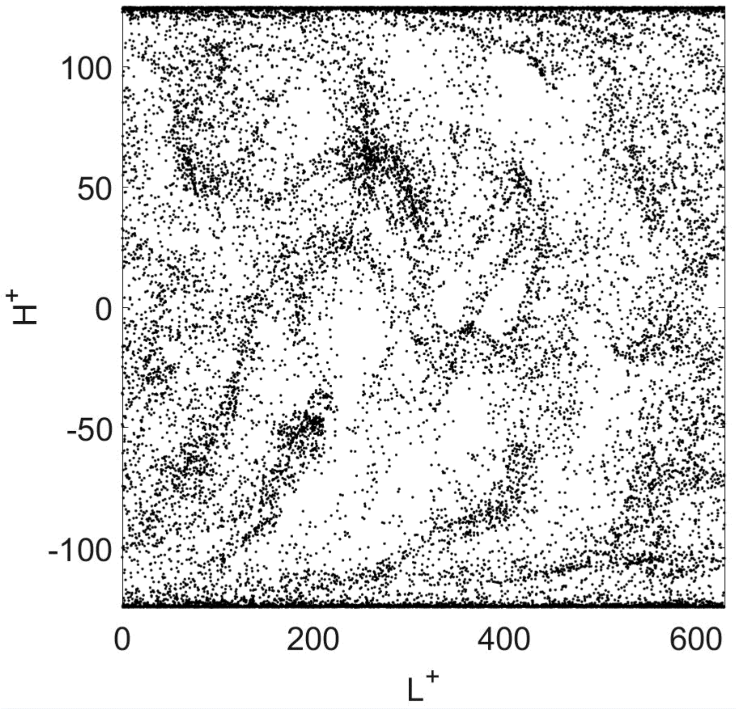
Normalwise direction



Streamwise direction

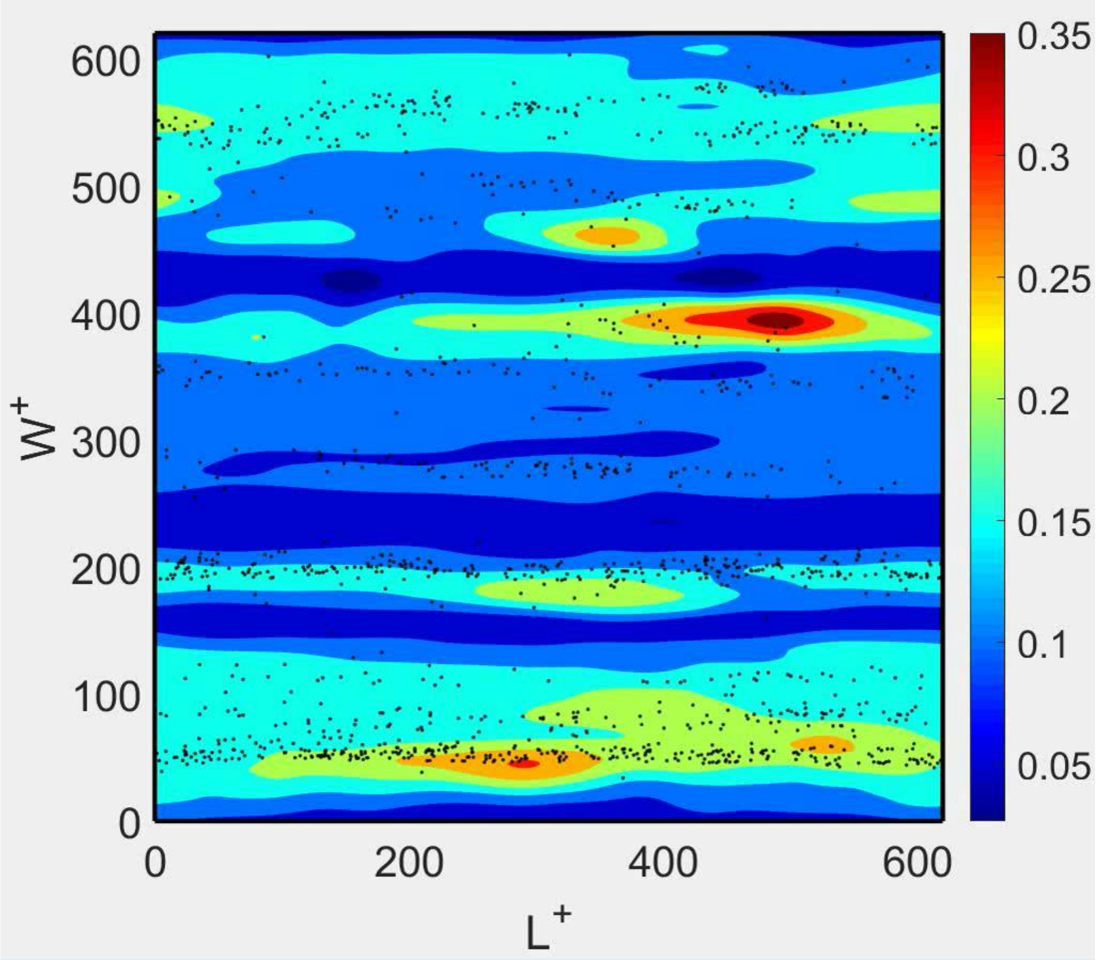


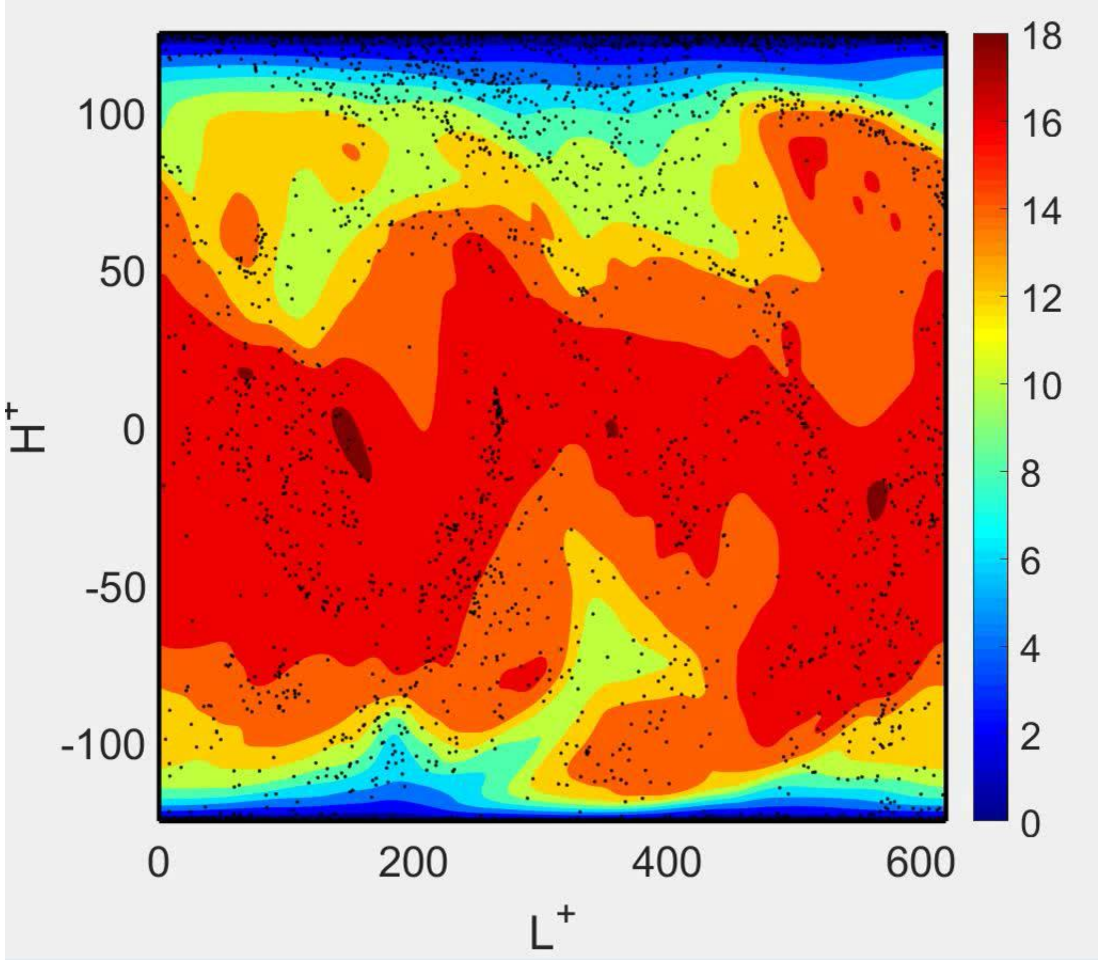
Spanwise direction



Space Variations

X-Velocity Contours with 30 μm particles

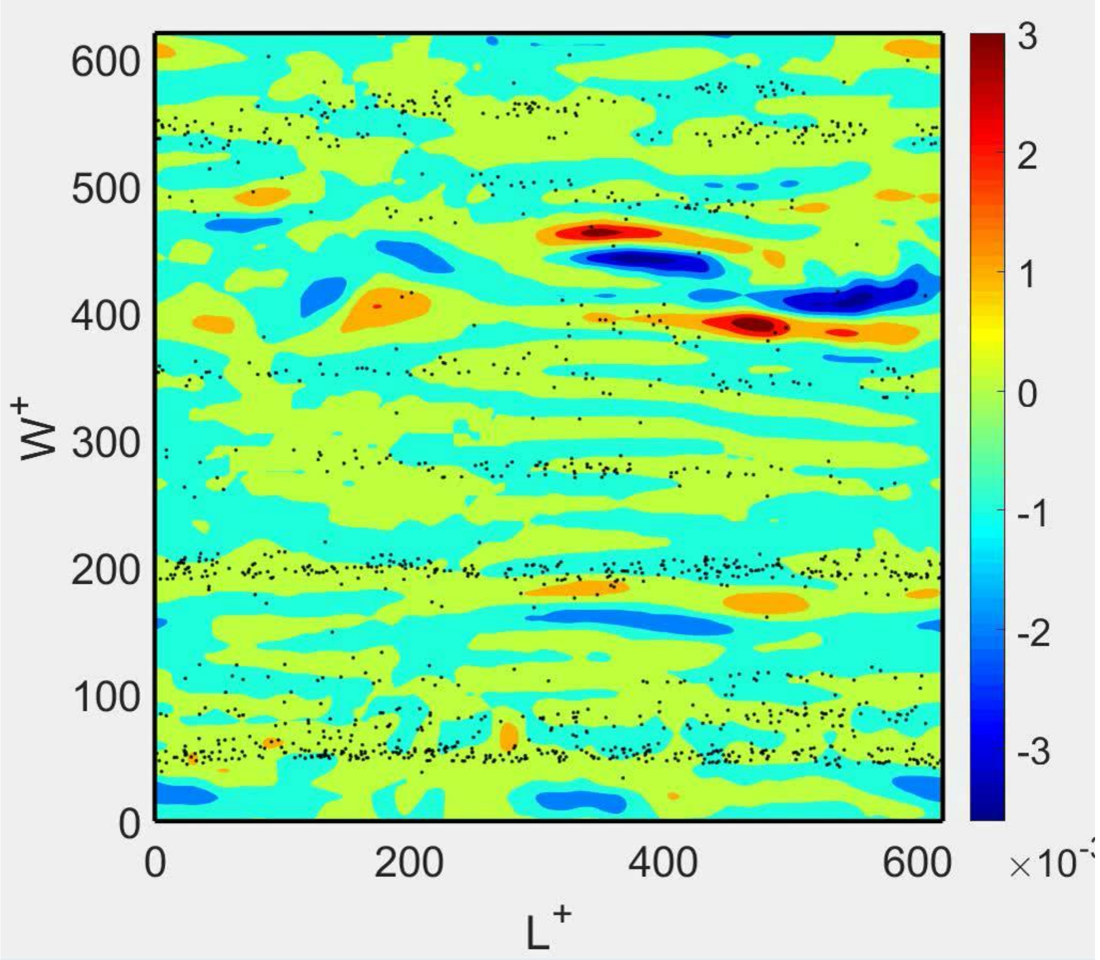




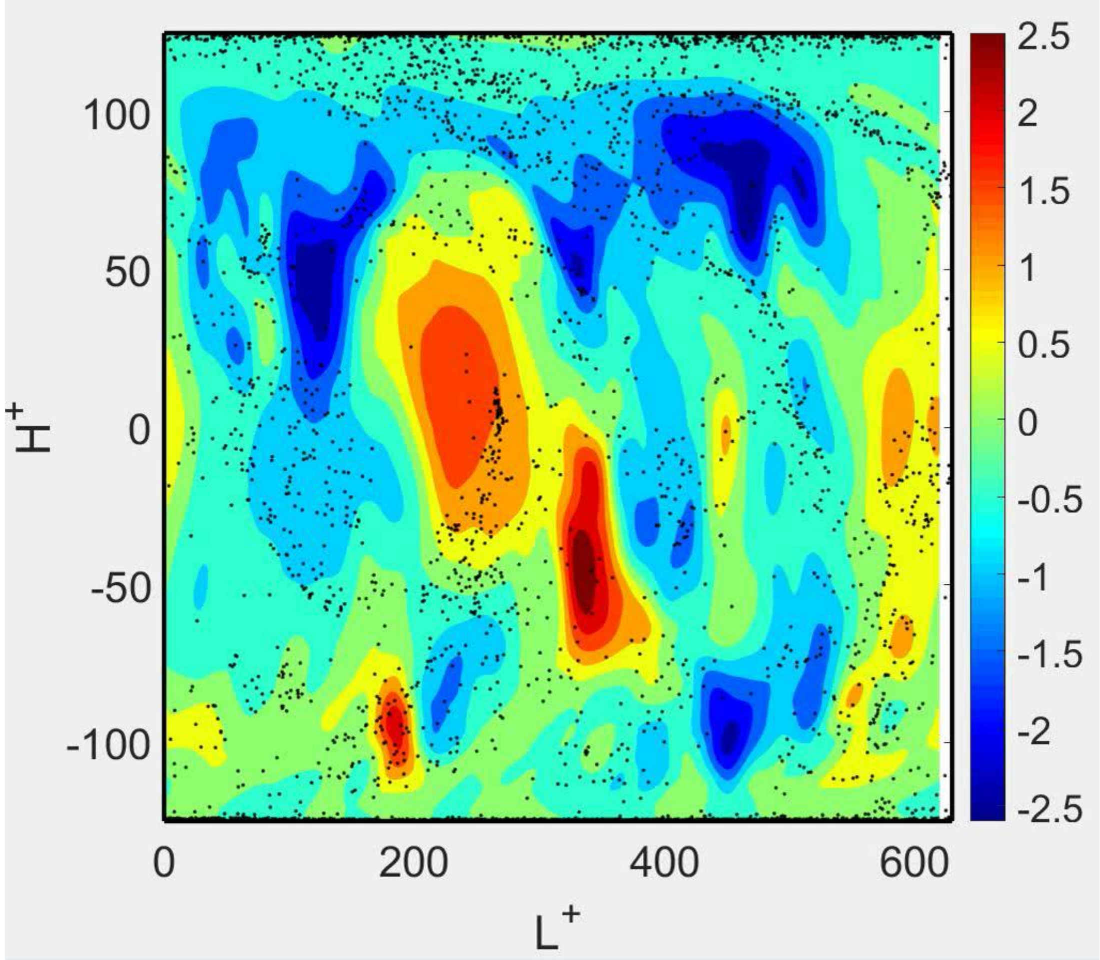
Normalwise direction

Spanwise direction

Y-Velocity Contours with 30 µm Particles

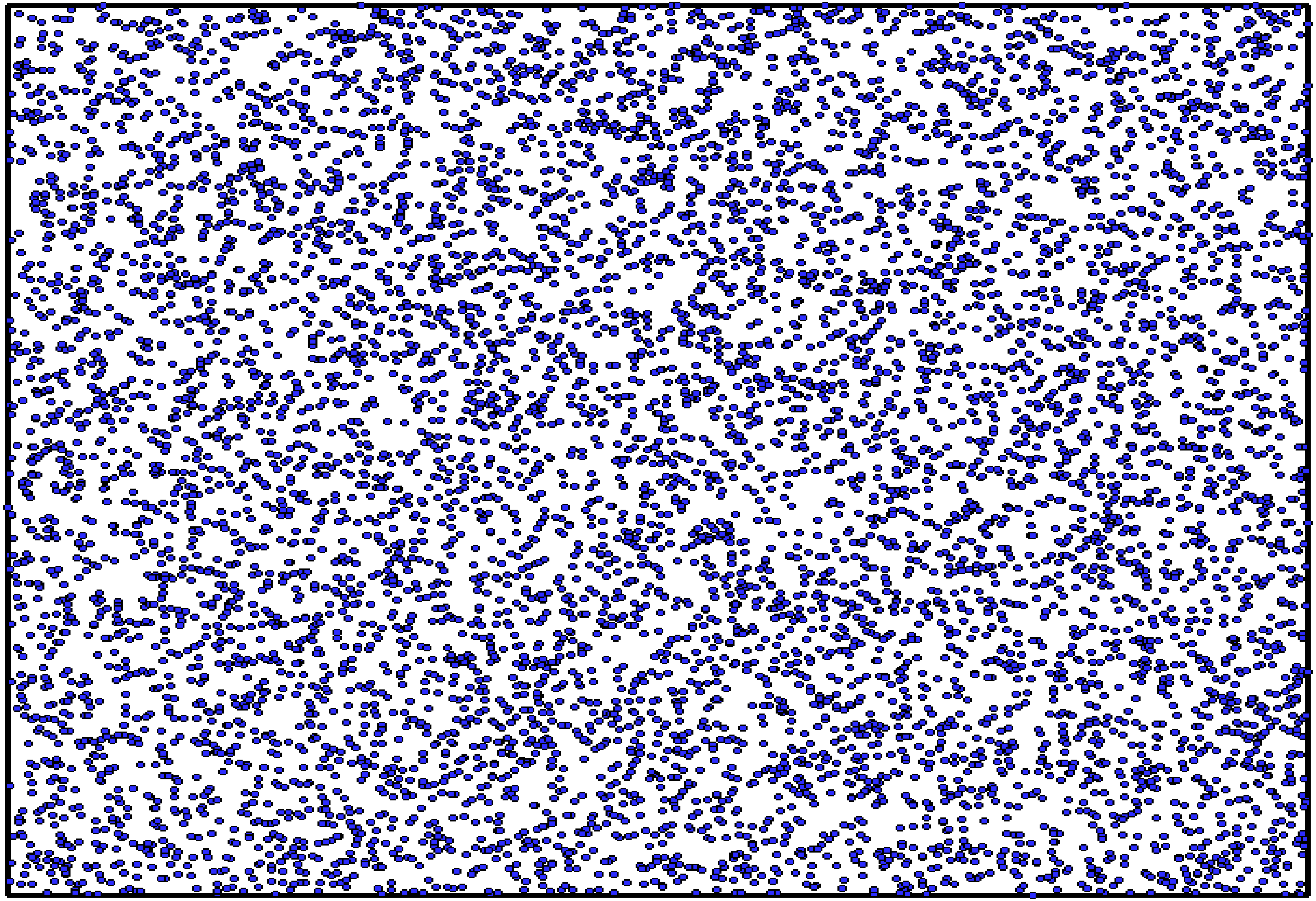


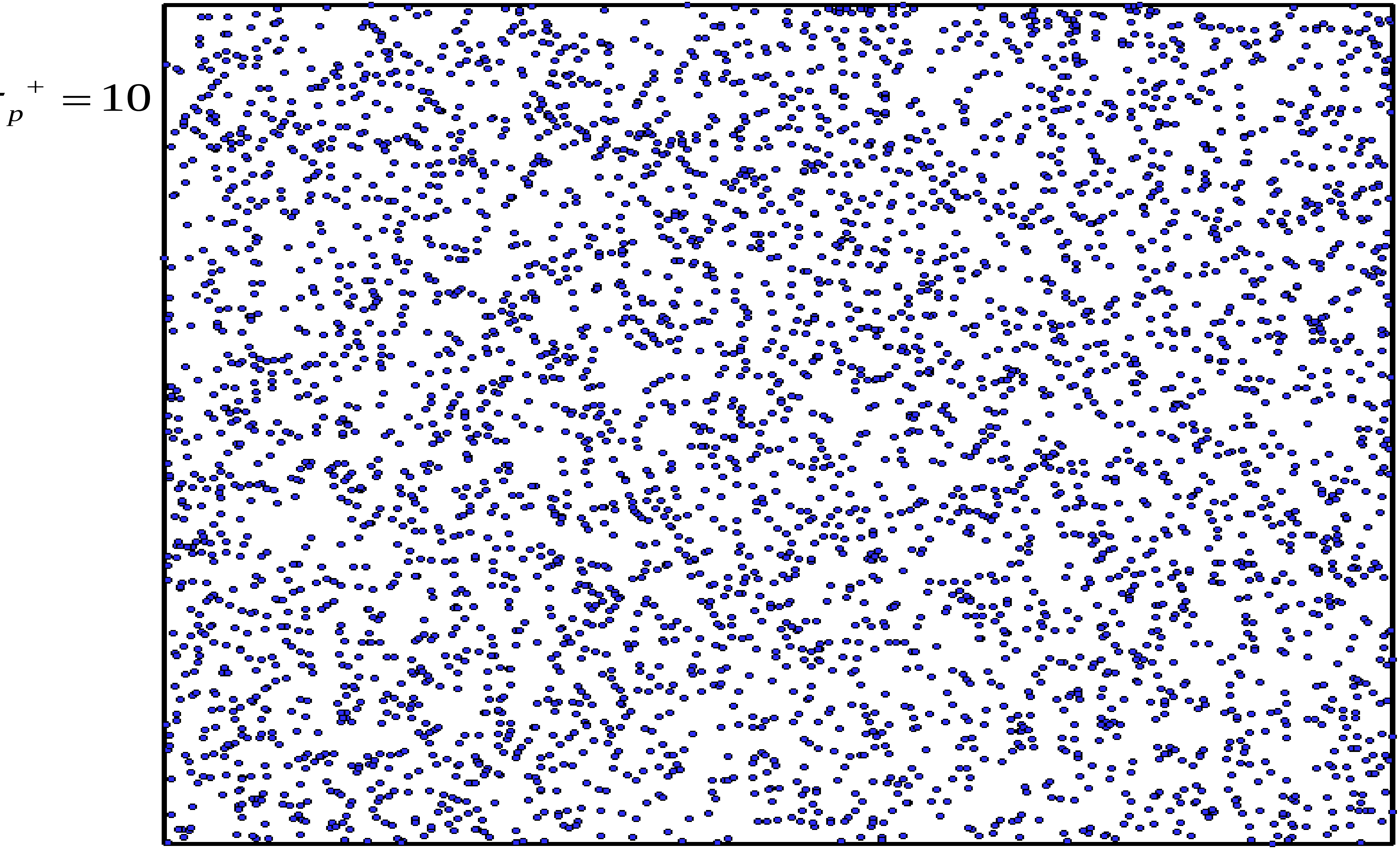
Normalwise direction



Spanwise direction

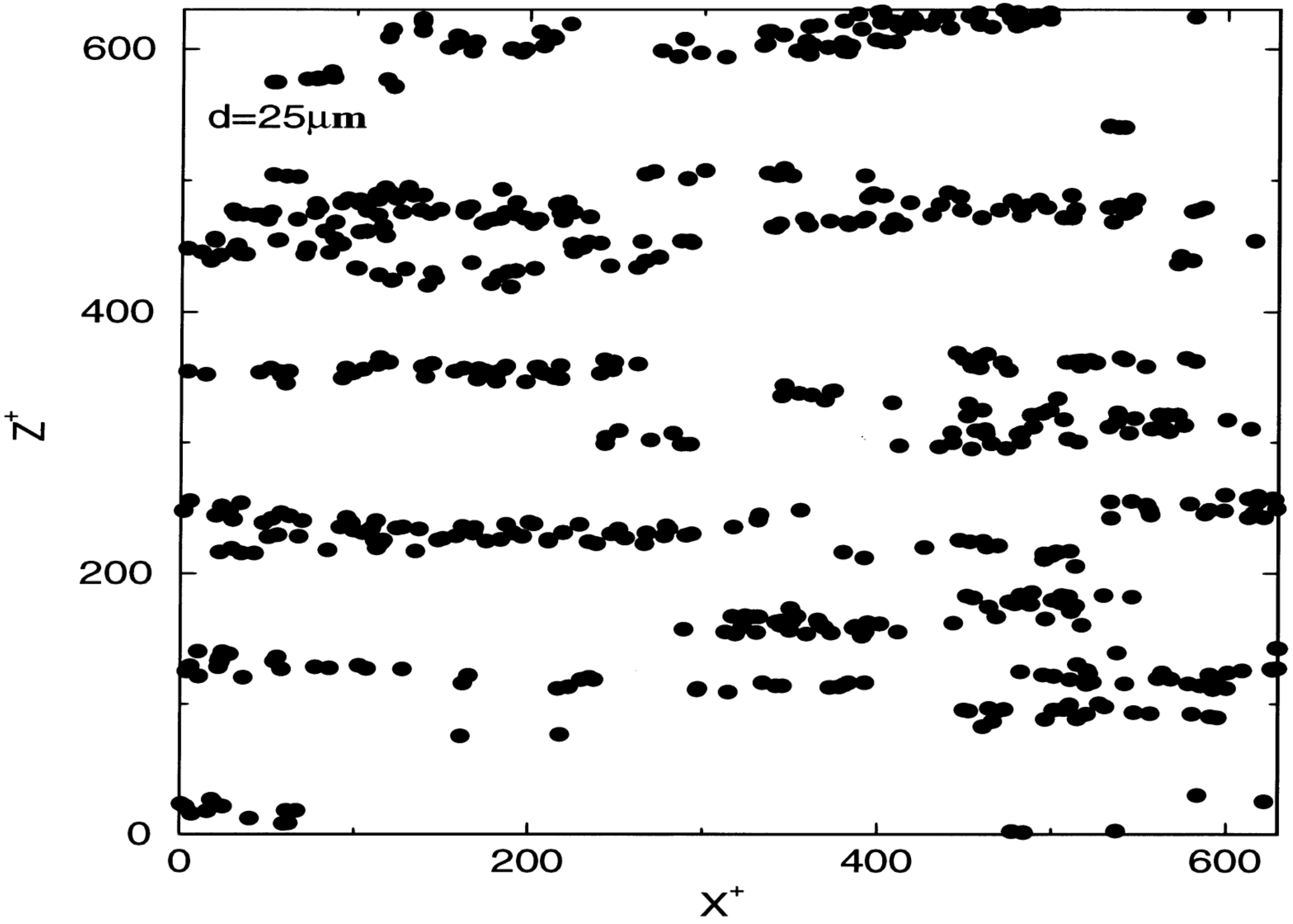
$\tau_p{}^+ = 10$




$\tau_p{}^+ = 10$

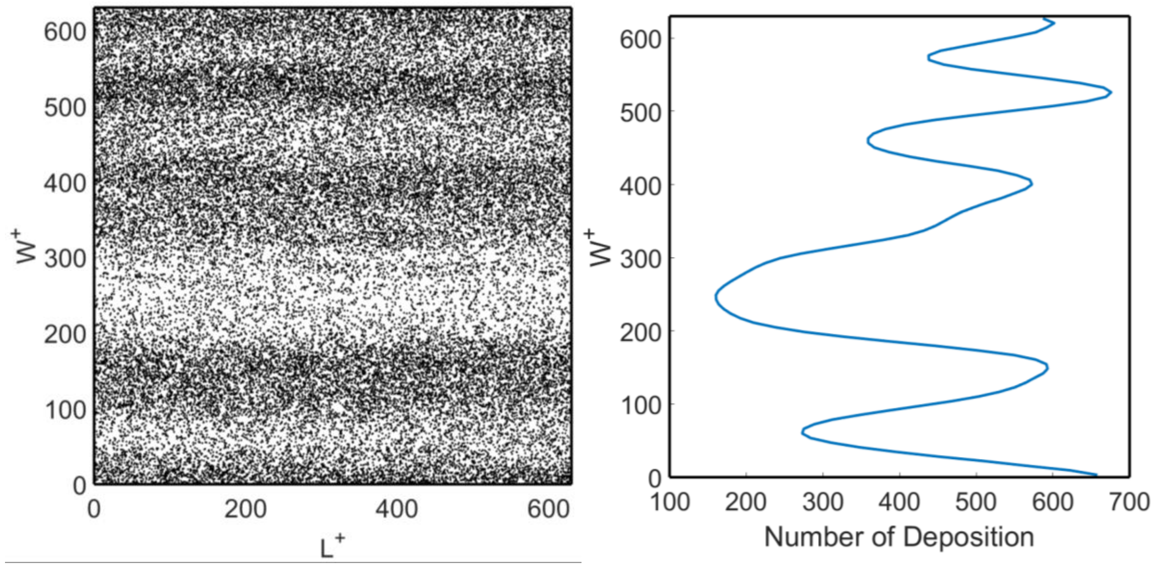
Deposition Pattern

Mean Flow Direction

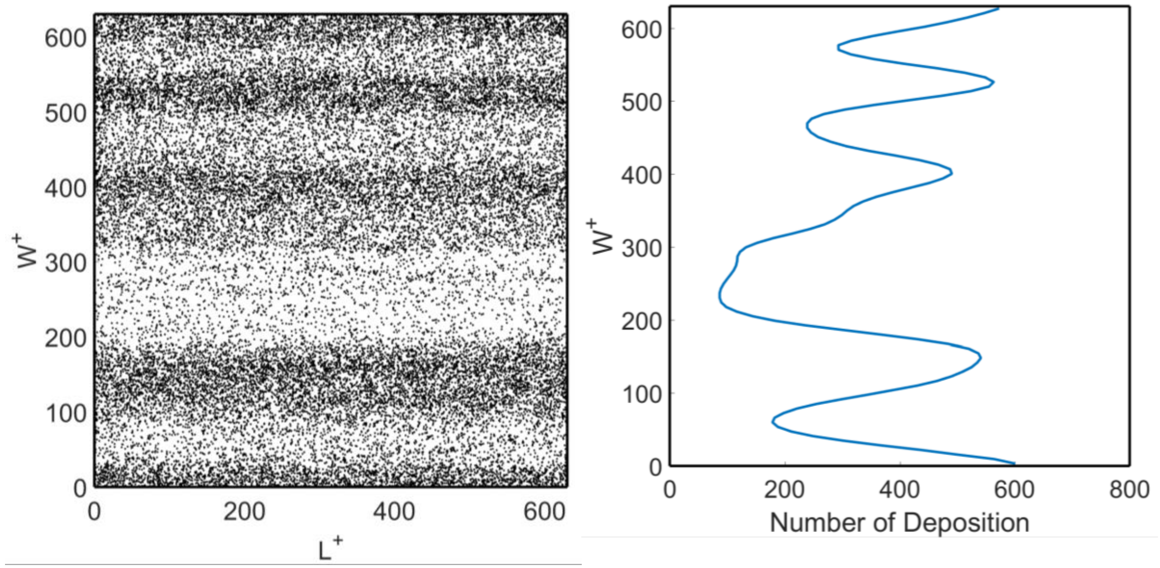


Pattern of Deposition on the Lower Wall

Dp=80 µm

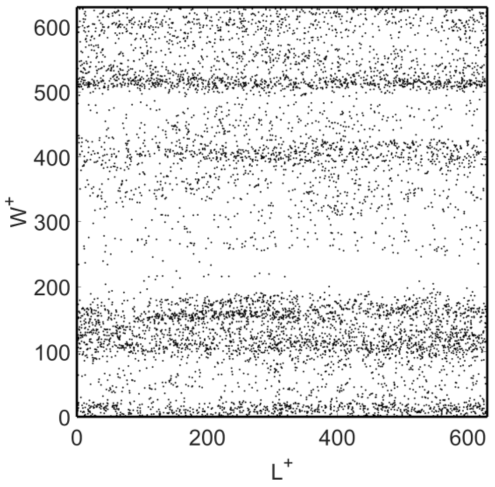


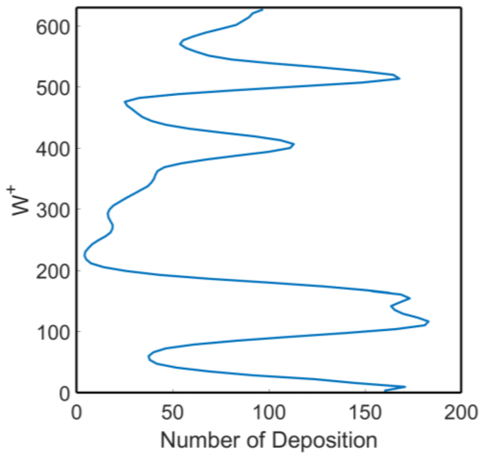
Dp=60 µm

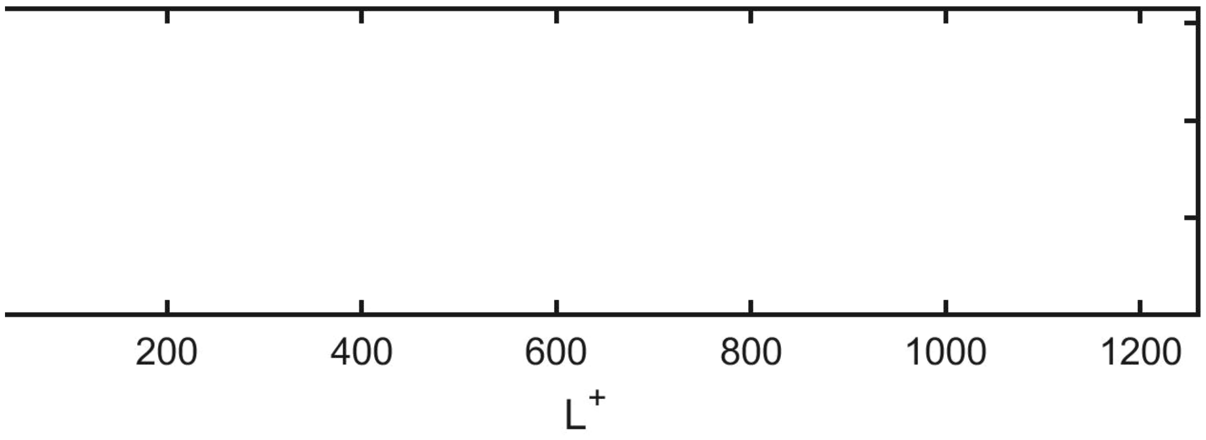


Pattern of Deposition on the Lower Wall

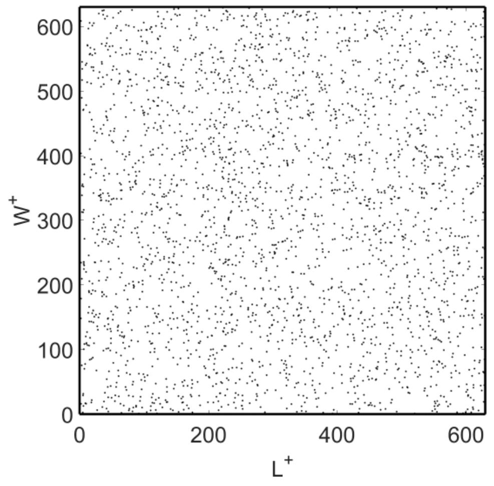
Dp=30 µm

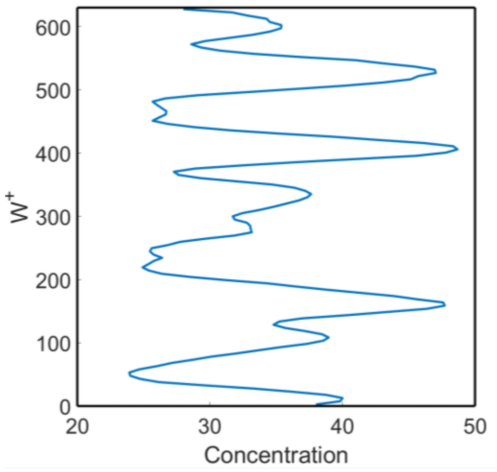


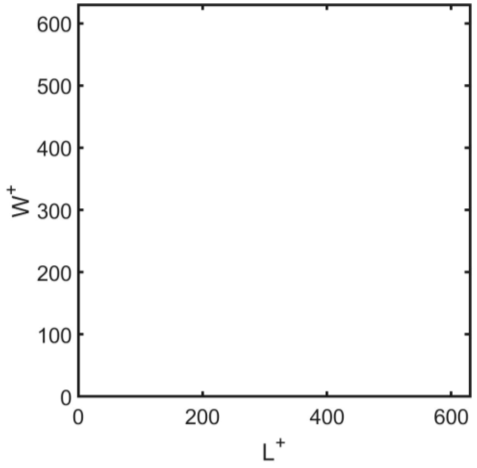




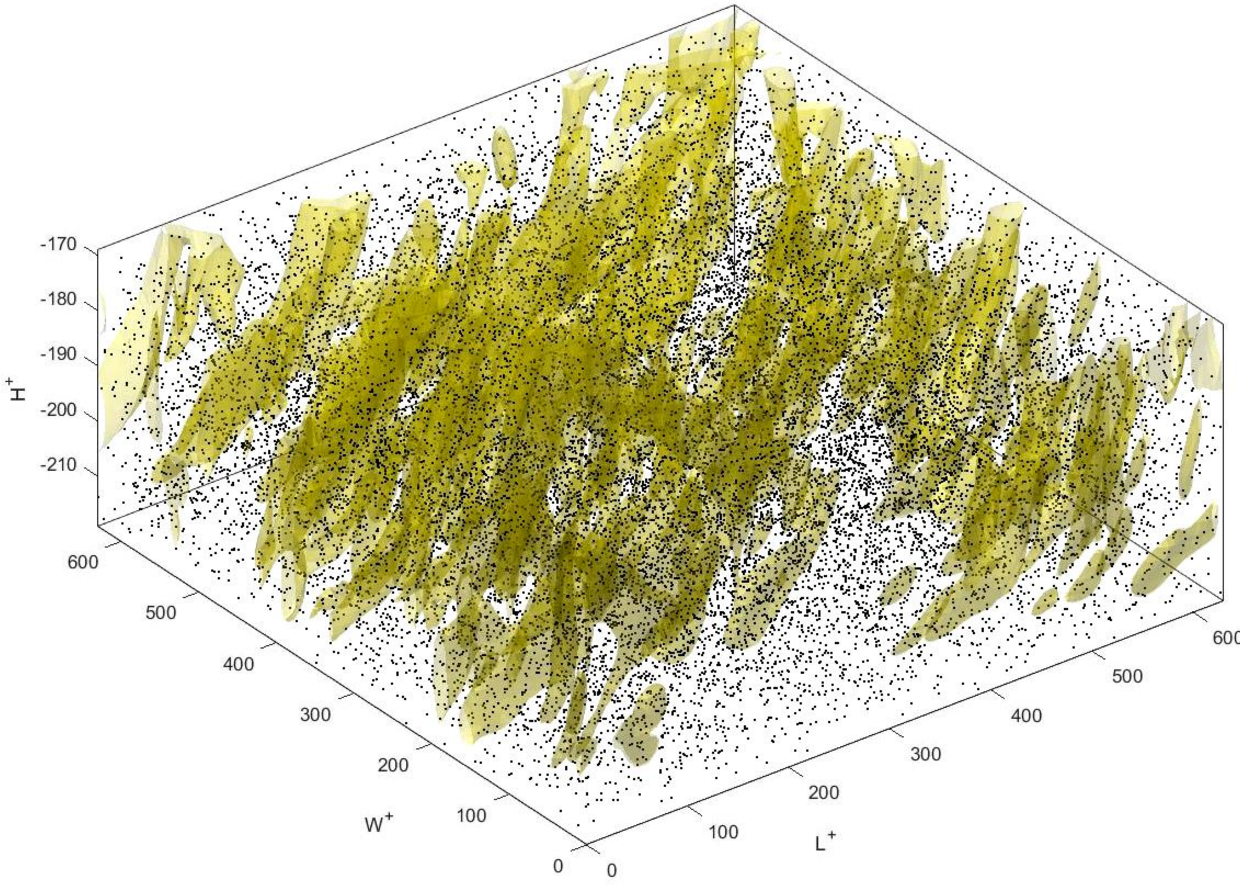
Dp=10 nm



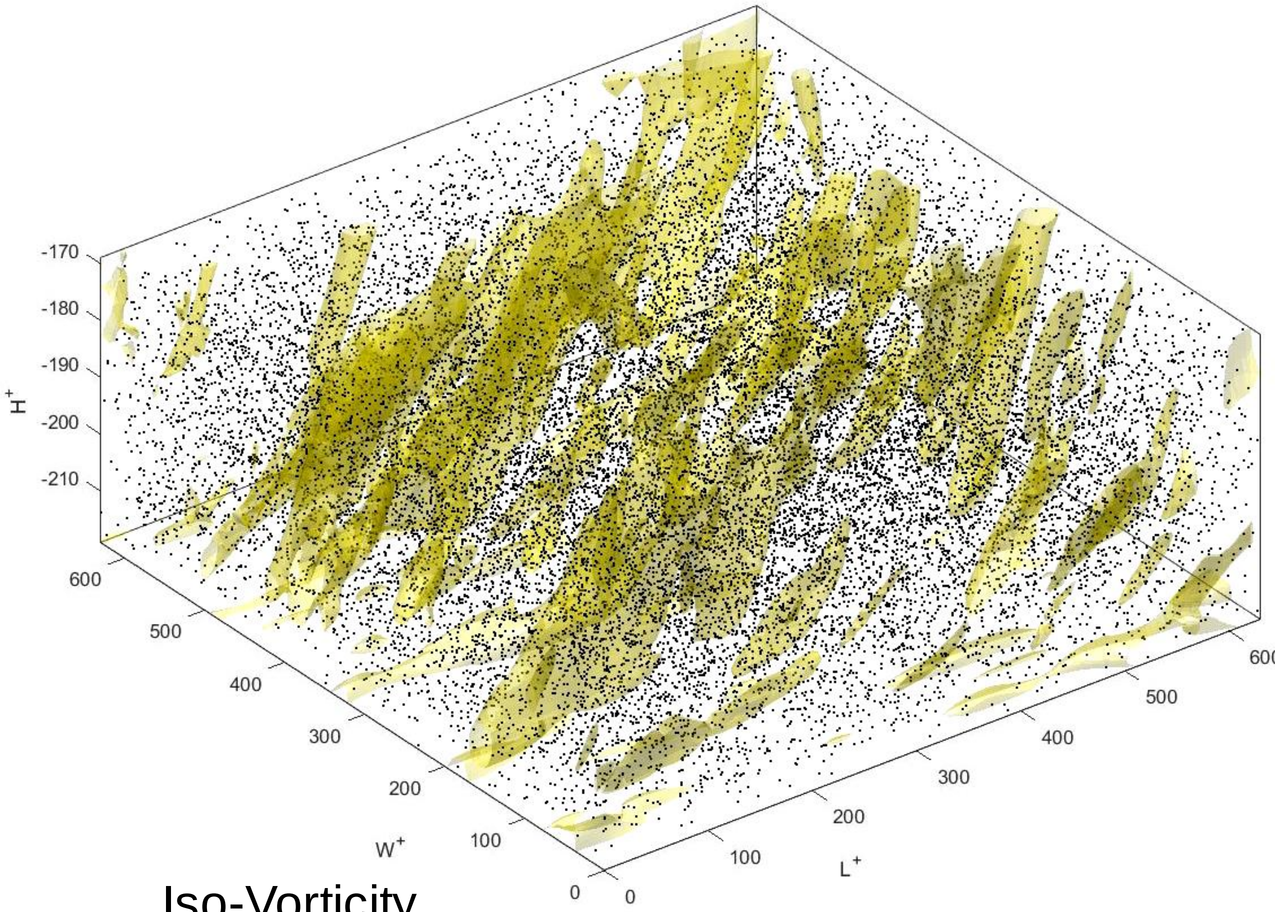




Iso-Q & Iso-Vorticity Contours



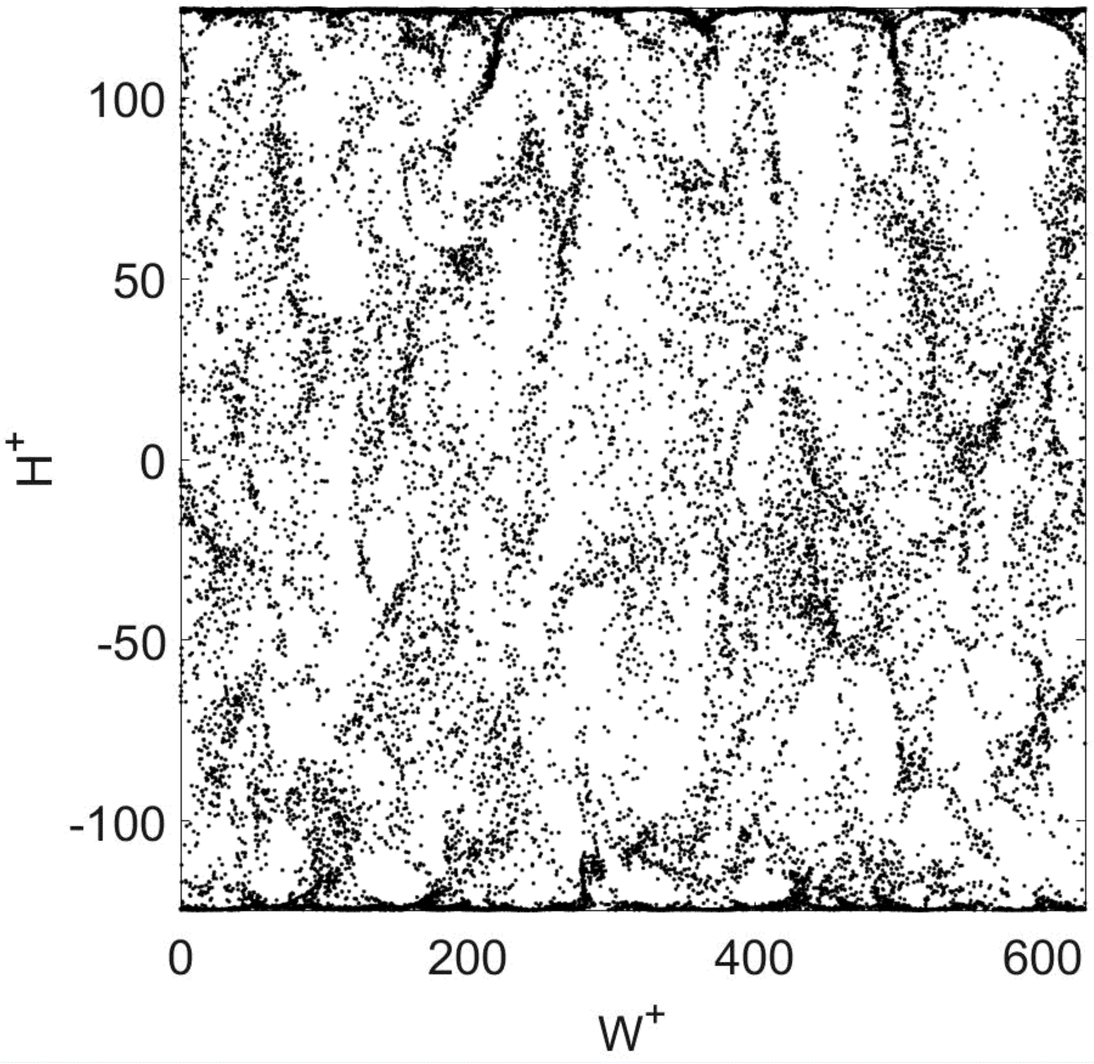
Iso-Q



Iso-Vorticity

Conclusions

- The **coherent near-wall turbulent structures** were visualized.
- The **turbophoresis effects** on particle concentration and velocity profiles were observed.
- For inertial particles with $\tau^{+} = 2 - 60$, the turbulence near-wall eddies control the near-wall **preferential concentration** and the particle **deposition process**.
- For larger or smaller particles, the preferential concentration patterns become smeared.



Questions